

# Meridional flow velocities on solar-like stars with known activity cycles

Dilyara Baklanova\*

*Crimean Astrophysical Observatory, Nauchny 298409, Crimea*

Sergei Plachinda

*Crimean Astrophysical Observatory, Nauchny 298409, Crimea*

## Abstract

The direct measurements of the meridional flow velocities on stars are impossible today. To evaluate the meridional flow velocities on solar-like stars with stable activity periods, we supposed that during the stellar Hale cycle the matter on surfaces of stars passes the meridional way equivalent to  $2\pi R_*$ . We present here the dependence of the mean meridional flow velocity on Rossby number, which is an effective parameter of the stellar magnetic dynamo.

**Keywords:** stars: solar-like; stars: activity; stars: Hale cycle; stars: meridional flow velocity

## 1. Introduction

Today the physics of the large-scale flows on the Sun and stars are intensively simulated by scientists to determine the detailed mechanisms of activity cycles. Recent results and bibliography are presented, for example, in the papers by Upton and Hathaway (2014), Zhao et al. (2013), Guerrero et al. (2013), Moss et al. (2013), Kitchatinov (2013), Kitchatinov and Olemskoy (2012).

The empirical dependence of the mean meridional flow speed on the number of the 22-year Hale cycle (Plachinda et al., 2011) was obtained under the assumption that during the Hale cycle the total length of the reverse track of the poloidal dipole polarity is equivalent to the circumference of the Sun as the magnetic dipole moment does not vanish and migrates between the poles (Livshits and Obridko, 2006; Moss et al., 2013).

The mean velocity  $\langle v \rangle = 6.29 \text{ m s}^{-1}$ , which gives  $P_{Hale} = 22$  years for the Sun, corresponds to the 7.3 years activity period for the solar-like star 61 Cyg A and is well agreed with the observations (Plachinda et al., 2011). Therefore we supposed that the magnetic flux transported by meridional flows on the surfaces of solar-like stars with stable activity period also passes the way equivalent to  $2\pi R_*$  during the own Hale cycle. We use this approach to draw the dependence of the mean meridional flow velocity on the Rossby number. In other words, in this paper we use the empirical data to see whether the duration of activity cycle on convective stars depends on the effective parameter of dynamo processes.

## 2. Parameters of stars

We selected stars with well-known activity periods. In the Table 1 and Table 2 we summarized the physical parameters of the stars that we have got from literature.

The names of the stars are listed in the first columns of the Tables. Columns 2-4 in the Table 1 contain magnitude  $V$ , spectral type and color index  $B - V$ . The rotation periods of the stars and the references are given in the 5th and 6th columns, the duration of activity cycles and the references are given in the 7th and 8th columns.

The masses of the stars and the references are listed in the 9th and 10th columns in the Table 1, columns 11 and 12 represent the radii of the stars and the references, columns 13-14 give the logarithm of gravity and the references. Finally, columns 15-16 show the effective temperature and the references.

The 2nd column in the Table 2 shows the parameter  $\langle R'_{HK} \rangle$  defined as the ratio of the chromospheric emission in the cores of the CaII H and K lines to the total bolometric emission of the star, and the 3rd column contains the references. The logarithm of the convective turnover time, the Rossby number obtained from the dependence of  $\tau_c$  from  $B - V$  and the mean meridional flow velocity are listed in the last three columns in the Table 2.

The convective turnover time  $\tau_c$  and the Rossby number were calculated using the methods described in the Section 3. The mean meridional flow velocity has been calculated using the equation  $2\pi R_*/\langle v \rangle = P_{Hale}$  (Plachinda et al., 2011), where  $R_*$  is the radius of a star,  $P_{Hale}$  is the stellar magnetic activity period,  $P_{Hale} = 2P_{cyc}$ , where  $P_{cyc}$  is a star-spot activity period. The mean activity period of the Sun calculated by averaging of sunspot numbers for all years of observations from 1755 to 2008 is equals to  $P_{cyc\odot} = 11$  years.

\*Corresponding author

Email address: dilyara@crao.crimea.ua (Dilyara Baklanova)

Table 1: Parameters of stars

Name	V	Sp	$B - V$	$P_{rot}$ , days	Ref <sup>a</sup>	$P_{cyc}$ , yr	Ref <sup>b</sup>	$M_*$ , $M_\odot$	Ref <sup>c</sup>	$R_*$ , $R_\odot$	Ref <sup>d</sup>	$\log g$	Ref <sup>e</sup>	$T_{eff}$ , K	Ref <sup>f</sup>
Sun		G2 V	0.65	25.4	5	11.0	—	1.00		1.00		4.44		5780	
BE Cet	6.39	G2 V	0.659	7.78	7	6.7	2	1	6	1.04	6	4.4	6	5790	6
54 Psc	5.87	K0 V	0.85	48.0	5	13.8	1	0.76	12	0.94	12	4.51	21	5250	28
HD4628	5.75	K2 V	0.88	38.5	7	8.37	1	0.77	6	0.69	6	4.64	6	5004	6
107 Psc	5.24	K1 V	0.84	35.2	7	9.6	1	0.816	21	0.82	21	4.54	21	5098	11
HD16160	5.82	K3 V	0.98	48.0	7	13.2	1	0.809	21	0.76	21	4.62	21	5262	29
$\kappa^1$ Cet	4.80	G5 V	0.68	9.214	2	5.9	2	1.02	6	0.877	6	4.5	16	5630	16
40o <sup>2</sup> Eri	4.43	K1 V	0.82	43.0	8	10.1	1	0.81	21	0.82	21	4.31	16	5090	16
HD32147	6.22	K3 V	1.06	47.4	9	11.1	1	0.838	21	0.78	21	4.4	18	4945	18
HD78366	5.93	F9 V	0.585	9.67	7	12.2	1	1.13	21	1.075	23	4.46	21	5938	23
HD81809	5.38	G2 V	0.64	18.0	13	8.17	1	1.33	14	2.24	14	3.86	14	5888	14
DX Leo	7.01	K0 V	0.78	5.377	10	3.21	2	0.93	11	0.84	11	4.4	18	5121	11
CF UMa	6.45	K1 V	0.75	31.0	8	7.3	1	0.661	21	0.681	17	4.63	21	4759	17
$\beta$ Com	4.26	F9.5 V	0.57	12.35	7	16.6	1	1.17	11	1.1	17	4.4	16	5960	16
HD115404	6.66	K2 V	0.93	18.47	11	12.4	1	0.86	11	0.77	11	4.3	25	4852	11
18 Sco	5.49	G2 V	0.652	23.7	9	7.1	3	1.01	24	1.03	24	4.4	27	5433	17
V2133 Oph	5.75	K2 V	0.827	21.07	7	17.4	1	0.91	15	0.84	15	4.5	18	5924	18
V2292 Oph	6.64	G7 V	0.76	11.43	11	10.9	1	0.97	11	0.87	9	4.56	21	5266	11
V2215 Oph	6.34	K5 V	1.16	18.0	11	21.0	1	0.72	11	0.63	11	4.67	9	4319	11
HD160346	6.52	K3 V	0.96	36.4	11	7.0	1	0.86	11	0.77	11	4.3	25	4862	11
HD166620	6.40	K2 V	0.87	42.4	7	15.8	1	0.89	11	0.791	21	4.0	18	5035	18
61 Cyg A	5.21	K5 V	1.18	35.37	7	7.3	1	0.69	20	0.665	20	4.63	6	4400	20
61 Cyg B	6.03	K7 V	1.37	37.84	7	11.7	1	0.605	20	0.595	20	4.71	21	4040	20
HN Peg	5.94	G0 V	0.587	4.86	7	5.5	2	1.1	21	1.041	21	4.48	21	5967	23
94 Aqr A	5.20	G8.5 IV	0.79	42.0	8	21.0	1	1.04	14	1.99	14	3.86	14	5370	14
94 Aqr B	8.88	K2 V	0.88	43.0	8	10.0	1	0.96	15	0.93	15	4.54	15	5136	15
BY Dra	8.07	K6 V	1.2	3.83	4	13.7	4	0.58	22	0.71	22	4.65	18	4622	18
V833 Tau	8.42	K5 V	1.19	1.7936	4	6.4	4	0.93	26	0.77	22	4.5	22	4450	22

<sup>a</sup>References for rotation periods; <sup>b</sup>References for periods of the activity cycles; <sup>c</sup>References for stellar masses; <sup>d</sup>References for radii of stars;

<sup>e</sup>References for  $\log g$ ; <sup>f</sup>References for effective temperatures  $T_{eff}$

(1) Baliunas et al. (1995); (2) Messina and Guinan (2002); (3) Hall et al. (2007); (4) Olah et al. (2000); (5) Noyes et al. (1984); (6) Cranmer and Saar (2011); (7) Donahue and Saar (1996); (8) Baliunas et al. (1996); (9) Cincunegui et al. (2007); (10) Messina et al. (1999); (11) Wright et al. (2011); (12) Santos et al. (2004); (13) Isaacson and Fischer (2010); (14) Allende Prieto and Lambert (1999); (15) Fuhrmann (2008); (16) Chmielewski (2000); (17) Boyajian et al. (2012); (18) Mishenina et al. (2012); (20) Kervella et al. (2008); (21) Takeda et al. (2007); (22) Eker et al. (2008); (23) Masana et al. (2006); (24) Lammer et al. (2012); (25) Soubiran et al. (2010); (26) Roser et al. (2011); (27) Mishenina et al. (2003); (28) Hillen et al. (2012); (29) van Belle and von Braun (2009)

### 3. The dependence of the Rossby number on the mean chromospheric emission ratio $\langle R'_{HK} \rangle$

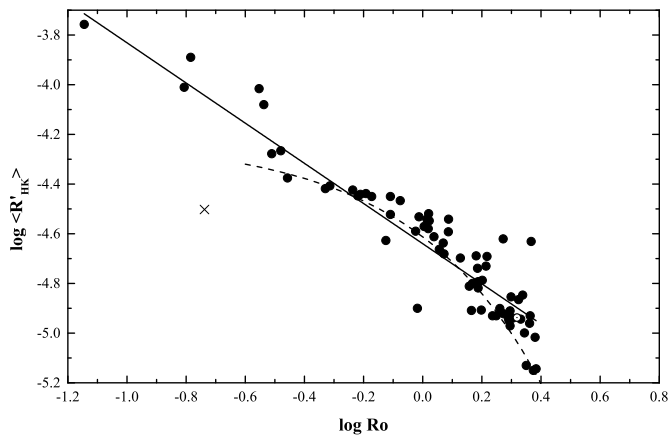


Figure 1:  $\log \langle R'_{HK} \rangle$  versus the logarithm of the Rossby number  $\log(P_{obs}/\tau_c)$ , where  $\tau_c = f(B - V)$ . The symbol  $\odot$  identifies the place of the Sun. The dashed line is the function from Noyes et al. (1984). The solid line represents the linear fit to all data except one point marked by the cross.

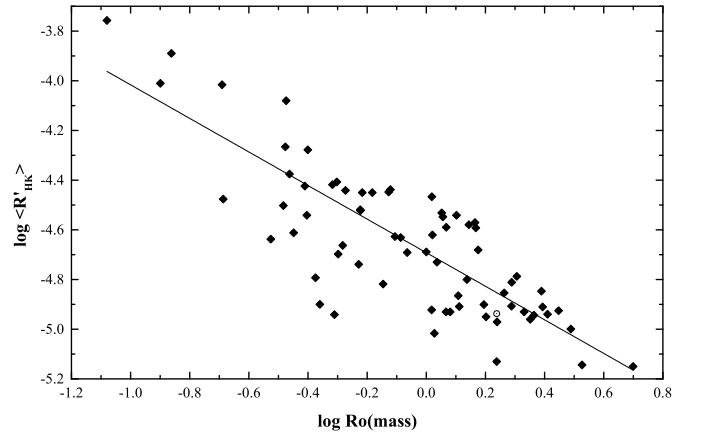


Figure 2:  $\log \langle R'_{HK} \rangle$  versus the logarithm of the Rossby number  $\log(P_{obs}/\tau_c)$ , where  $\tau_c = f(M_*)$ . The symbol  $\odot$  points out the place of the Sun. The solid line represents the linear fit to all data points.

The Rossby number,  $Ro = P_{rot}/\tau_c$ , is the ratio of the stellar rotation period  $P_{rot}$  to the convective turnover time  $\tau_c$ . To find the convective turnover time Noyes et al. (1984, eq. 4) used the empirical dependence of  $\tau_c$  on color index  $B - V$ , and Wright et al. (2011) chose the empirical de-

Table 2: Parameters of stars

Name	$\log \langle R'_{HK} \rangle$	Ref <sup>g</sup>	$\log \tau_c$	Ro	$v$ , m s <sup>-1</sup>
Sun	-4.937	5	1.08	2.080	6.92
BE Cet	-4.441	5	1.10	0.616	7.91
54 Psc	-4.960	5	1.32	2.297	4.72
HD4628	-4.852	5	1.29	1.988	5.71
107 Psc	-4.874	5	1.31	1.722	5.84
HD16160	-4.847	5	1.34	2.179	4.46
$\kappa^1$ Cet	-4.45	16	1.14	0.672	10.29
40o <sup>2</sup> Eri	-4.944	5	1.30	2.145	5.55
HD32147	-4.94	5	1.37	2.013	5.05
HD78366	-4.631	5	0.62	2.327	6.10
HD81809	-4.907	5	1.06	3.596	18.98
DX Leo	-4.08	18	1.27	0.290	18.12
CF UMa	-4.930	5	1.24	1.772	6.46
$\beta$ Com	-4.756	5	0.88	1.636	4.61
HD115404	-4.467	5	1.35	0.840	4.58
18 Sco	-4.950	19	1.08	1.983	11.31
V2133 Oph	-4.541	5	1.31	0.544	3.34
V2292 Oph	-4.438	5	1.25	0.643	5.53
V2215 Oph	-4.627	5	1.38	0.750	2.08
HD160346	-4.787	5	1.36	1.589	7.62
HD166620	-4.910	5	1.33	1.974	3.72
61 Cyg A	-4.800	5	1.38	1.473	6.31
61 Cyg B	-4.909	5	1.42	1.461	4.02
HN Peg	-4.424	5	0.92	0.580	13.11
94 Aqr A	-4.999	5	1.28	2.209	6.56
94 Aqr B	-4.902	5	1.34	1.952	6.44
BY Dra	-4.01	18	1.39	0.156	3.59
V833 Tau	—	—	1.39	0.076	8.33

<sup>g</sup>References for  $\log R'_{HK}$

(5) Noyes et al. (1984); (16) Chmielewski (2000);

(18) Mishenina et al. (2012); (19) Raghavan et al. (2010)

pendence of  $\tau_c$  on stellar masses.

The dependence of  $\log \langle R'_{HK} \rangle$  on  $\log Ro$  for  $\tau_c = f(B - V)$  according to Noyes et al. (1984) is shown in Figure 1 by dashed curve. The dependence of  $\log \langle R'_{HK} \rangle$  on  $\log Ro$ , where  $\tau_c = f(M_*)$ , is plotted in Figure 2.

The relation between  $\log \langle R'_{HK} \rangle$  and  $\log Ro$  is more accurate in the case of using of the dependence of  $\tau_c$  on color index  $B - V$ . The significance level of the difference between the scatterings is more than 99.99%. Therefore we used the relation  $\tau_c = f(B - V)$  to evaluate the Rossby number.

We have supplemented the list of stars of Noyes et al. (1984) using, in particular, the stars with higher level of the chromospheric activity. The relation between  $\log \langle R'_{HK} \rangle$  and  $\log Ro$  in this case may be presented as  $\log R'_{HK} = -4.63 - 0.83 \log Ro$  (solid line in Figure 1).

#### 4. The dependence of the mean meridional flow velocity on the Rossby number and the activity cycle period

The Figure 3 shows that the mean meridional flow velocities  $\langle v \rangle$  for solar-type stars located near  $5.4 \pm 1.5$  m s<sup>-1</sup> that is in good agreement with the mean value of the meridional flow velocity of the Sun ( $6.29$  m s<sup>-1</sup>, (Plachinda et al., 2011)) obtained in the same manner. We could suggest that the mean meridional flow velocity does not depend on the Rossby number. The only five stars out of 28

show higher values which significantly (more than  $3\sigma$ ) deviates from the mean value of the meridional flow velocity. So, we can suppose that in the case of 80% stars with the stable activity period the meridional flow determines the duration of the Hale's cycle.

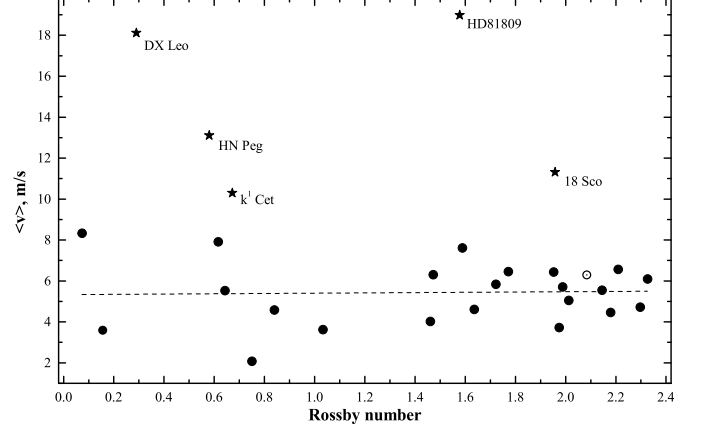


Figure 3: Mean meridional flow velocity versus Rossby number. The dotted line is a fit to all data excluding 5 points (stars symbols) which lie out of  $10$  m s<sup>-1</sup>.

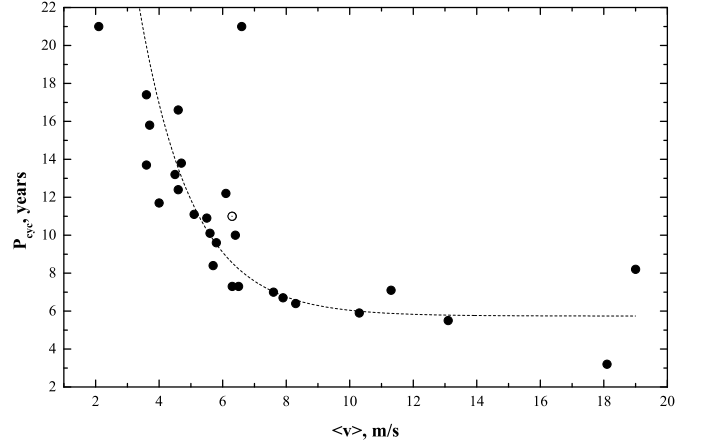


Figure 4:  $P_{cyc}$  versus mean meridional flow velocity  $\langle v \rangle$ .

On the other hand, Figure 4 demonstrates that the observed cycle period shows the exponential decay when the velocity of the flow increases. The relation between  $P_{cyc}$  and  $\langle v \rangle$  may be presented as  $P_{cyc} = 5.74 + 35 \exp(-(\langle v \rangle - 2.1)/1.66)$  (dashed line in Figure 4).

The dynamo models show qualitatively similar but much slower decay (see Bonanno et al., 2002, Figure 8). Therefore, we can not eliminate another way to interpret the detected velocity as the phase velocity of the dynamo wave drift (e.g., Kitchatinov, 2002).

#### 5. Acknowledgement

We thank both anonymous referees and V. Butkovskaya for their constructive comments and useful suggestions.

## References

- Allende Prieto, C., Lambert, D.L., 1999. Fundamental parameters of nearby stars from the comparison with evolutionary calculations: masses, radii and effective temperatures. *Astronomy and Astrophysics* 352, 555–562.
- Baliunas, S. L. et al., 1995. Chromospheric variations in main-sequence stars. *The Astrophysical Journal* 438, 269–287.
- Baliunas, S.L., Sokoloff, D., Soon, W.H., 1996. Magnetic Field and Rotation in Lower Main-Sequence Stars: An Empirical Time-Dependent Magnetic Bode’s Relation? *The Astrophysical Journal* 457, 99–102.
- van Belle, G.T., von Braun, K., 2009. Directly Determined Linear Radii and Effective Temperatures of Exoplanet Host Stars. *The Astrophysical Journal* 694, 1085–1098.
- Bonanno, A., Elstner, D., Rudiger, G., Belvedere, G., 2002. Parity properties of an advection-dominated solar  $\alpha$  2 Omega-dynamo. *Astronomy and Astrophysics* 390, 673–680.
- Boyajian, T. S. et al., 2012. Stellar Diameters and Temperatures. I. Main-Sequence a, F, and G Stars. *The Astrophysical Journal* 746, 101.
- Chmielewski, Y., 2000. The infrared triplet lines of ionized calcium as a diagnostic tool for F, G, K-type stellar atmospheres. *Astronomy and Astrophysics* 353, 666–690.
- Cincunegui, C., Diaz, R.F., Mauas, P.J.D., 2007. H $\alpha$  and the Ca II H and K lines as activity proxies for late-type stars. *Astronomy and Astrophysics* 469, 309–317.
- Cranmer, S.R., Saar, S.H., 2011. Testing a Predictive Theoretical Model for the Mass Loss Rates of Cool Stars. *The Astrophysical Journal* 741, 54.
- Donahue, R.A., Saar, S.H., 1996. A relationship between mean rotation period in lower main-sequence stars and its observed range. *The Astrophysical Journal* 466, 384–391.
- Eker, Z. et al., 2008. A catalogue of chromospherically active binary stars (third edition). *Monthly Notices of the Royal Astronomical Society* 389, 1722–1726.
- Fuhrmann, K., 2008. Nearby stars of the Galactic disc and halo IV. *Monthly Notices of the Royal Astronomical Society* 384, 173–224.
- Guerrero, G., Smolarkiewicz, P.K., Kosovichev, A.G., Mansour, N.N., 2013. Differential rotation in solar-like stars from global simulations. *The Astrophysical Journal* 779, 176.
- Hall, J.C., Lockwood, G.W., Skiff, B.A., 2007. The Activity and Variability of the Sun and Sun-like Stars. I. Synoptic Ca II H and K Observations. *The Astronomical Journal* 133, 862–881.
- Hillen, M., Verhoeft, T., Degroote, P., Acke, B., van Winckel, H., 2012. The dynamic atmospheres of Mira stars: comparing the CODEX models to PTI time series of TU Andromedae. *Astronomy & Astrophysics* 538, L6.
- Isaacson, H., Fischer, D., 2010. Chromospheric Activity and Jitter Measurements for 2630 Stars on the California Planet Search. *The Astrophysical Journal* 725, 875–885.
- Kervella, P., Merand, A., Pichon, B., 2008. The radii of the nearby K5V and K7V stars 61 Cyg A & B-CHARA/FLUOR interferometry and CESAM2k modeling. *Astronomy & Astrophysics* 488, 667–674.
- Kitchatinov, L., Olemskoy, S.V., 2012. Differential rotation of main-sequence dwarfs: predicting the dependence on surface temperature and rotation rate. *Monthly Notices of the Royal Astronomical Society* 423, 344–3351.
- Kitchatinov, L.L., 2002. The direction of propagation of the solar dynamo wave. *Astronomy Letters* 28, 626–631.
- Kitchatinov, L.L., 2013. Theory of differential rotation and meridional circulation, in: Kosovichev, A.G., de Gouveia Dal Pino, E.M., Y., Y. (Eds.), *Solar and Astrophysical Dynamos and Magnetic Activity*, Proceedings of the International Astronomical Union, IAU Symposium, volume 294, pp. 399–410.
- Lammer, H. et al., 2012. Variability of solar/stellar activity and magnetic field and its influence on planetary atmosphere evolution. *Earth, Planets and Space* 64, 179–199.
- Livshits, I.M., Obridko, V.N., 2006. Variations of the dipole magnetic moment of the sun during the solar activity cycle. *Astronomy Reports* 50, 926–935.
- Masana, E., Jordi, C., Ribas, I., 2006. Effective temperature scale and bolometric corrections from 2MASS photometry. *Astronomy and Astrophysics* 450, 735–746.
- Messina, S., Guinan, E.F., 2002. Astrophysics Magnetic activity of six young solar analogues I. Starspot cycles from long-term photometry. *Astronomy & Astrophysics* 393, 225–237.
- Messina, S., Guinan, E.F., Lanza, A.F., Ambruster, C., 1999. Activity cycle and surface differential rotation of the single Pleiades star HD 82443 (DX Leo). *Astronomy and Astrophysics* 347, 249–257.
- Mishenina, T.V., Kovtyukh, V.V., Korotin, S.A., Soubiran, C., 2003. Sodium Abundances in Stellar Atmospheres with Differing Metallicities. *Astronomy Reports* 47, 422–429.
- Mishenina, T.V., Soubiran, C., Kovtyukh, V.V., Katsova, M.M., Livshits, M.A., 2012. Activity and the Li abundances in the FGK dwarfs. *Astronomy & Astrophysics* 547, A106.
- Moss, D., Kitchatinov, L.L., Sokoloff, D., 2013. Reversals of the solar dipole. *Astronomy and Astrophysics* 550, L9.
- Noyes, R.W., Hartmann, L.W., Baliunas, S.L., Duncan, D.K., Vaughan, A.H., 1984. Rotation, convection, and magnetic activity in lower main-sequence stars. *The Astrophysical Journal* 279, 763–777.
- Olah, K., Kollath, Z., Strassmeier, K.G., 2000. Multiperiodic light variations of active stars. *Astronomy and Astrophysics* 356, 643–653.
- Plachinda, S., Pankov, N., Baklanova, D., 2011. General Magnetic Field of the Sun as a star (GMF): Variability of the frequency spectrum from cycle to cycle. *Astronomische Nachrichten* 332, 918–924.
- Raghavan, D. et al., 2010. A Survey of Stellar Families: Multiplicity of Solar-Type Stars. *The Astrophysical Journal Supplement Series* 190, 1–42.
- Roser, S., Schilbach, E., Piskunov, A.E., Kharchenko, N.V., Scholz, R.D., 2011. A deep all-sky census of the Hyades. *Astronomy & Astrophysics* 531, A92.
- Santos, N.C., Israelian, G., Mayor, M., 2004. Spectroscopic [Fe/H] for 98 extra-solar planet-host stars. Exploring the probability of planet formation. *Astronomy and Astrophysics* 415, 1153–1166.
- Soubiran, C., Le Campion, J.F., Cayrel de Strobel, G., Caillo, A., 2010. The PASTEL catalogue of stellar parameters. *Astronomy and Astrophysics* 515, A111.
- Takeda, G., Ford, E.B., Sills, A., Rasio, F.A., Fischer, D.A., Valenti, J.A., 2007. Structure and Evolution of Nearby Stars with Planets. II. Physical Properties of ~1000 Cool Stars from the SPOCS Catalog. *The Astrophysical Journal Supplement Series* 168, 297–318.
- Upton, L., Hathaway, D.H., 2014. Predicting the Sun’s Polar Magnetic Fields with a Surface Flux Transport Model. *The Astrophysical Journal* 780, id. 5.
- Wright, N.J., Drake, J.J., Mamajek, E.E., Henry, G.W., 2011. The Stellar-activity-Rotation Relationship and the Evolution of Stellar Dynamos. *The Astrophysical Journal* 743, 48.
- Zhao, J., Bogart, R.S., Kosovichev, A.G., Duvall, T. L., J., Hartlep, T., 2013. Detection of equatorward meridional flow and evidence of double-cell meridional circulation inside the Sun. *The Astrophysical Journal* 774, L29.